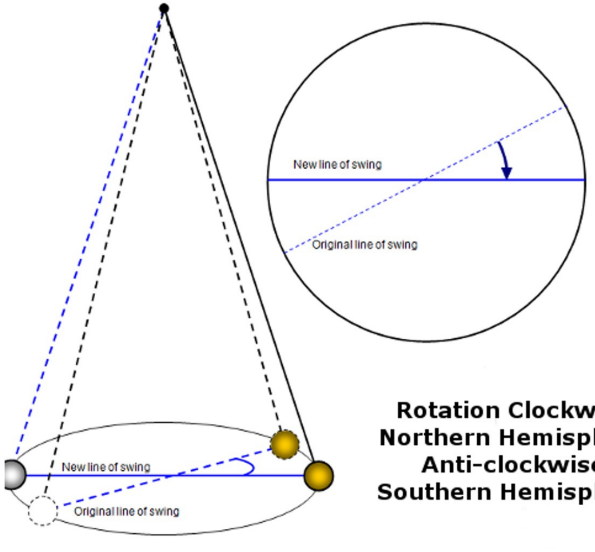
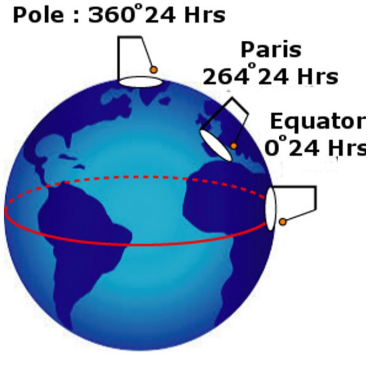
Foucault Pendulum



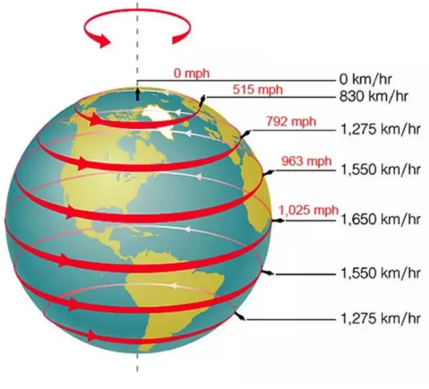
Rotation Clockwise
Northern Hemisphere
Anti-clockwise
Southern Hemisphere



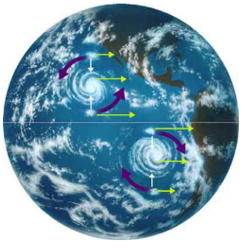
A pendulum is hung from a fixed place and set to swing in a plane. The fixed point is obviously moving with the earth. So what happens to the plane in which the pendulum is swinging. {Picture above} First, imagine doing this experiment at the north pole. The fixed point of the pendulum is directly above the axis of the earth. The thread does not rotate with the earth. So the plane appears to complete one revolution in twenty four hours. Next imagine doing the experiment at the equator. The fixed point moves along with the earth. So the angle between the plane of movement of the pendulum and other objects around it does not change, a complete rotation takes infinite time. As we move from the equator to the pole, the time taken for the plane of the pendulum to complete one rotation decreases from infinity to twenty four hours.

In reality, the plane of movement of the pendulum cannot change because there is no force that can cause such a rotation. Newton's law is not violated. Because the earth rotates, the plane appears to change. Leon Foucault used this experiment to show that we can see the earth rotate. Foucault pendulums are a big attraction in many science museums. They are more than 25 meters long, have a heavy weight attached at the bottom and carefully built to swing for a long time. The swinging pendulum knocks down small wooden pegs placed in a circle, one by one. If the Foucault pendulum is set up at the town of Kuruskhetra in India, which is on the 30^{o}N latitude, it completes one clockwise rotation in 48 hours. If the same is set up at 30^{o}S, it completes one rotation anti-clockwise, again in 48 hours. It would take 28 hours and 12 minutes to complete one rotation at the Arctic circle. The changes are another proof that the earth is a sphere. Calculating the time taken by a Foucault Pendulum to complete a rotation at any given latitude is an elementary high school physics problem.

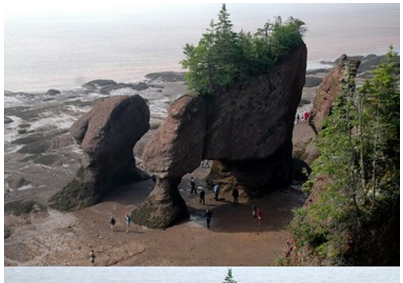
As earth rotates once every 24 hours, everything on the surface also moves. Not merely hills and trees but also water in the oceans and the air around the earth. The circumference of the earth at the equator is nearly 40000 kilometers. So everything there is moving that distance in 24 hours. Average speed is nearly 1600 km per hour. {Picture right}. But the tropics of Cancer or Capricorn are only 37000 km long. The Arctic circle is only 18000 km long. So objects at the tropic or at the Arctic circle travel a much smaller distance in 24 hours. Average speed is lower. When air moves north from the equator towards the tropics, its speed has to decrease. So the air is pushed to



the right. If the air moves south the air is pushed to the left. This is called Coriolis effect. Due to this, the cyclonic storms north of the equator rotate clockwise. The storms south of the equator rotate counter clockwise.{Picture right}



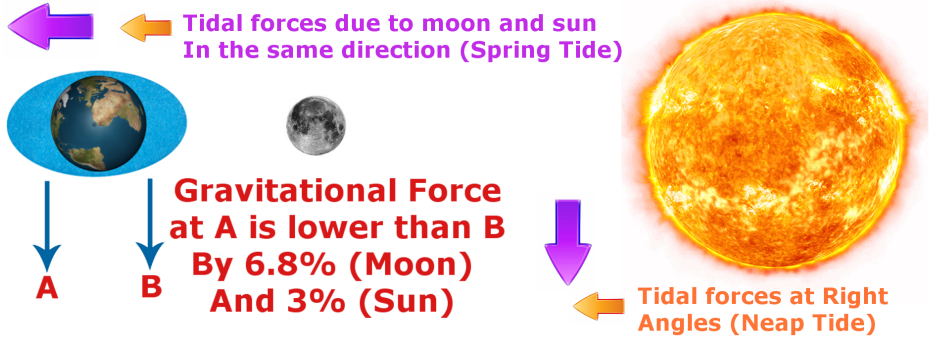
There are claims that just like the storms, north and south of the equator, water draining out of bath tubs and wash basins rotates in opposite directions, But this is not correct. The Coriolis effect is very weak. It can only be seen in storms because they are up to several hundred kilometers in diameter. If Coriolis effect was observable at small distances, participants in archery competitions should learn to aim in different directions for hitting the targets placed in different directions. But no one ever had to do so.



The acceleration due to gravity of the earth is the same at all places on the earth if they are at the sea level. The acceleration due to gravity is slightly lower at the top of the hill and so the water flows down. Then why does the sea level increase every few hours and then decrease again? {Picture left} In some places these changes are quite large and large boulders are seen submerged in the sea at one time and on dry land a few hours later. Curiously these changes are much larger on full moon and new moon days

A week later they are a bit less. These changes are called the tides. They are caused by the gravitational forces of the sun and the moon. As discussed earlier, the gravitational force between two bodies decreases to one fourth the value when the distance is doubled. The distance between the moon and the earth's surface facing it is shorter than that of the earth's surface directly opposite. {Picture below} The difference is the diameter of the earth. So the gravitational force of the moon on water facing the moon is more than on the water diametrically opposite by about 8%. Assume for simplicity that the earth is covered on all sides by a layer of water.

Because of the 8% difference in the gravitational force, the circular layer gets elongated in the direction of the moon. As the earth rotates, the elongation will always be facing the moon. The water in areas at right angles to the moon moves towards this direction and there is a "high" tide. In the direction perpendicular to the moon, there is "low" tide. In a twenty four hour period, at any pace there should be two high and two low tides. The sun also causes tides. But the effect of the sun on the tides is much smaller than the effect due to the moon. This appears surprising. After all the moon's mass is 1% of the earth's mass and the sun's mass is more than

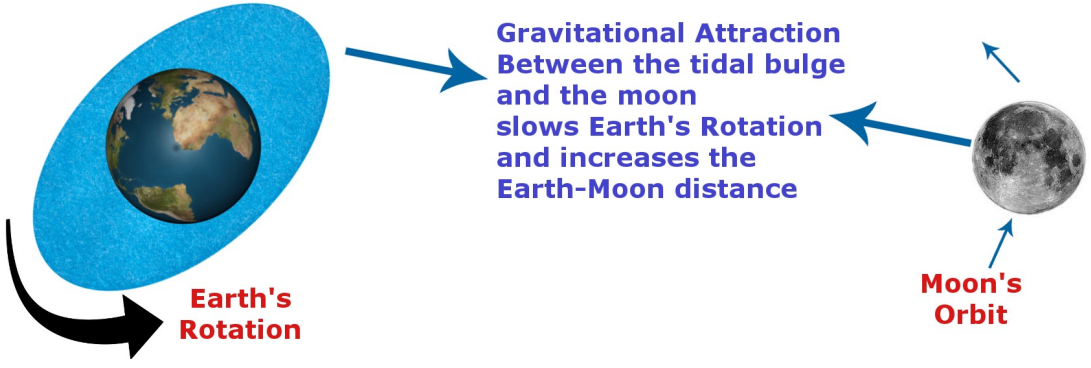


300000 times the mass of the earth and we said earlier that larger the mass, larger the gravitational force. But the sun is much further from the earth than the moon. The diameter of the earth is roughly one thirtieth the distance between the earth and moon. But the sun to earth distance is more than ten thousand times the earth's diameter. So the difference in gravitational force between the two sides of the earth is much larger in the case of the moon. It is the difference that is important for tides not the total force.

As mentioned before, on full moon day the earth is between the sun and the moon. On new moon day the moon is between the earth and the sun. So the tides caused by sun and moon add to one another and the "spring tide" is particularly large, {Picture opposite page} Midway through the fortnight, the sun and moon are at right angles, so their tides oppose each other and the "neap tide" is particularly low.

Observation of two tides per day and large tides during full and new moons can be explained by the simple idea of the water forming a layer around the earth. All the places facing the moon do not have a high tide exactly at the same time. Calculating the time of high and low tides at a given place is not very easy. There are several reasons for this. Continents and islands obstruct the movement of water. Speed of water movement depends on the depth. Shallow water, near the coast does not move as fast as deep water further from land. Also the speed of water moving along with the earth reduces as we move away from the equator. All these change the time of high and low tides as well as their size at different places.

Coriolis effect is the result of water and air at different distances from the equator moving at different speeds along with the rotating earth. The gravitational force of the moon on the

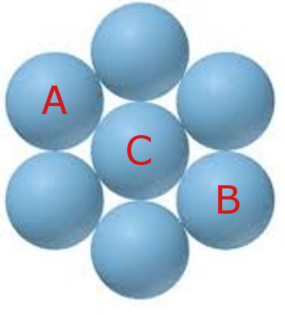


bulge of high tide, opposes the movement of water along with the earth. This results in a small frictional loss. {Picture above} We can now measure time down to a billionth of a second, using modern atomic clocks. These show that the time taken by the earth to complete one rotation is decreasing by about 0.0002 seconds per year due to this frictional loss. Because of this the moon is moving away from the earth by about 4cm per year. While the length of the day is changing, the year, the time taken by the earth to complete one rotation around the sun is not observed to change. Measuring such small changes and explaining their causes is the strength of modern science.

There are two parts of Newton's law of gravitation. First, the gravitational force becomes one fourth the earlier value when the distance between two objects doubles. Second, when the mass of one of the two objects doubles the force also doubles. The force of gravity can be felt at infinitely large distances. Though the sun is 8 light minutes or 150 million kilometers away, the earth moves in an ellipse around the sun because the sun is 300000 times heavier than the earth. The sun is one star among a trillion stars in the milky way

galaxy. The sun is at a distance of some thirty thousand light years from the center of the galaxy. Because the center is a million times heavier, the sun is also moving around the center and is estimated to complete one rotation in about 20 million years. Jupiter is about three thousand times heavier than the earth but it is very far. The scientist rejects astrology pointing out that the mother is much nearer than planet Jupiter and would exert a larger gravitational force on the just born baby.

If both objects have mass, there will always be a gravitational force between them. Between every pair of small parts of the earth and the moon, there will be gravitational forces. What we call the gravitational force between the earth and the moon is the sum of these uncountable numbers of gravitational forces. It is important to remember that the gravitational force between a pair of bodies is not reduced, blocked or changed by the presence of other bodies between them. Sphere C {Picture below} does not effect the gravitational forces between spheres A and B. During a solar eclipse for example, the moon does not block the gravitational force of the sun. As mentioned before, the gravitational forces of the sun and moon add and cause larger tides. Gravitational shields that can help us fly without rockets do not exist in nature, only in fantasy stories.



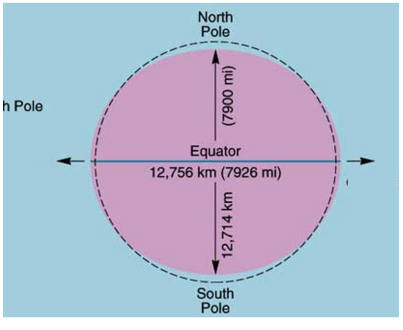
There are two ways in which the gravitational force between the earth and the moon can be calculated. The simplest method is to assume that all the mass of the earth is concentrated at its center, that all the mass of the moon is concentrated at its center and the distance between the earth and the moon is just the distance between the centers. Then the force can be easily calculated. Another method is

to divide both the earth and the moon into extremely large numbers of small parts, determine the gravitational force between each pair and sum them all up. A modern mathematical method called calculus is used to perform this calculation. Both methods give the same answer. This is very surprising and also most important. The mass of the earth is not really concentrated at its center. But assuming that it is true seems to work. The calculations made agree with experiments. For example it was said earlier that when a pendulum 25 cm long is taken from the sea level to a height of 1000meters, it loses 16 seconds in a day. To calculate this, we have to use the distances of sea level and the place 1000m higher from the center of the earth.

But suppose we take the same pendulum 1000m closer to the center by going down a mine? To determine how much the pendulum will lose and what the acceleration due to gravity at the bottom of the mine is, we need to use calculus. We will realize that the top 1000 m thick layer of the earth will not contribute to the gravitational force. Though the distance to the center of the earth decreased, the mass of the earth causing the gravitational force has also decreased. The acceleration due to gravity is lower than at sea level. If you do the mathematics completely we realize that the acceleration at a height of 1000m is equal to that at a depth of 2000m.

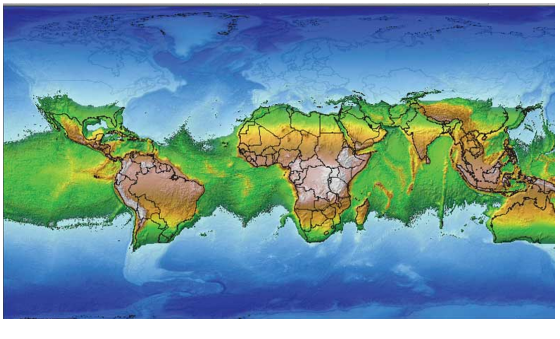
All over the earth, acceleration due to gravity is the same at the sea level. However, the sea level is not always at the same distance from the center of the earth. This is a result of the earth being not a perfect sphere. {Picture opposite page} The diameter of the earth from north pole to south pole is slightly smaller than the diameter at the equator. The earth is slightly compressed along the axis. This simple fact is the basis of a big pseudo scientific argument regarding the flow of the river Nile. The source of the Nile is nearer to the center

Not farther from the center of the earth than the source. At sea level.



Altititude 1135 m above sea level

of the earth than the place at which the river flows into the Mediterranean sea. The river also flows across the equator. This looks like the river flowing up and down on a small picture of the globe. From this, some people conclude that the earth is not a sphere and the theory of gravitation is wrong. The source of the Nile, lake Victoria is 1135 m above the sea level. The river water flowing into the sea is not a surprise at all. The mistake in this pseudo science is to measure the height of the source not from the sea level but from the center of the earth. To conclude that the acceleration due to gravity would increase as you get closer to the center is also wrong. We should note that the sea level is marked on a rotating earth. If you spin a wet ball, the water comes out to form a circular wheel around it. Similarly, because the earth is rotating, water accumulates around the equator and that is the sea level we observe. If by a miracle, the earth stops rotating, the water will flow towards the poles, leaving a huge new continent at the equator. {Picture right}



Using the Nile river as an example to question the theory of gravitation is an example of the confusion created by not understanding the basis of mathematical physics.